Software uncertainty in integrated environmental modelling: the role of semantics and open science

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Software Uncertainty in Integrated Environmental Modelling: the role of Semantics and Open Science

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Computational aspects increasingly shape environmental sciences [1]. Actually, transdisciplinary modelling of complex and uncertain environmental systems is challenging computational science (CS) and also the science-policy interface [2–7]. Large spatial-scale problems falling within this category – i.e. wide-scale transdisciplinary modelling for environment (WSTMe) [8–10] – often deal with factors **(a)** for which deep-uncertainty [2,7,11,12] may prevent usual statistical analysis of modelled quantities and need different ways for providing policy-making with science-based support.

Here, practical recommendations are proposed for tempering a peculiar – not infrequently underestimated – source of uncertainty. Software errors in complex WSTMe may subtly affect the outcomes with possible consequences even on collective environmental decision-making. Semantic transparency in CS [2,8,10,13,14] and free software [15,16] are discussed as possible mitigations **(b)**.

(a)

Complexity =
- Transdisciplinary integration (e.g. systems of systems)
- Environmental system(s) heterogeneity (e.g. geospatial fragmentation)
- Data heterogeneity (formats, definitions, spatiotemporal density, ...)
- Software complexity (algorithms, dependencies, languages, interfaces, ...)

Uncertainty =
- Incomplete scientific knowledge
  (e.g. climate scenarios [17–19], tipping points [20–23], ...)
- Modelling assumptions and simplifications [24–26]
- Uncertainty of measured/derived data
- Software uncertainty

Dynamic behaviour =
- Uncertainty propagation via:
  - Propagation in the network of interconnected WSTMe components [2,14,27–33]
  - Iterations within nonlinear optimization steps [5,34–40]
  - Data fusion, harmonization, integration [9,41–44]
  - Steps for computing and aggregating criteria and indices [6,7,11,12,45–48]

Software uncertainty, black-boxes and free software

Integrated natural resources modelling and management (INRMM) [28] frequently exploits chains of nontrivial data-transformation models (D-TM), each of them affected by uncertainties and errors. Those D-TM chains may be packaged as monolithic specialized models, maybe only accessible as black-box executables (if accessible at all) [49]. For end-users, black-boxes merely transform inputs in the final outputs, relying on classical peer-reviewed publications for describing the internal mechanism. While software tautologically plays a vital role in CS, it is often neglected in favour of more theoretical aspects. This paradox has been provocatively described as “the invisibility of software in published science. Almost all published papers required some coding, but almost none mention software, let alone include or link to source code” [50].

Recently, this primacy of theory over reality [51–53] has been challenged by new emerging hybrid approaches [54] and by the growing debate on open science and scientific knowledge freedom [2,55–58]. In particular, the role of free software has been underlined within the paradigm of reproducible research [49,57–59]. In the spectrum of reproducibility, the free availability of the source code is emphasized [57] as the first step from non-reproducible research (only based on classic peer-reviewed publications) toward reproducibility. Applying this paradigm to WSTMe, an alternative strategy to black-boxes would suggest exposing not only final outputs but also key intermediate layers of data and information along with the corresponding free software D-TM modules. A concise, semantically-enhanced modularization [13,14] may help not only to see the code (as a very basic prerequisite for semantic transparency) but also to understand – and correct – it [60]. Semantically-enhanced, concise modularization is e.g. supported by semantic array programming (SemAP) [13,14] and its extension to geospatial problems [8,10]. Some WSTMe may surely be classified in the subset of software systems which “are growing well past the ability of a small group of people to completely understand the content”, while “data from these systems are often used for critical decision making” [51]. In this context, the further uncertainty arising from the unpredicted “(not to say unpredictable)” [52] behaviour of software errors propagation in WSTMe should be explicitly considered as software uncertainty [61,62].

$Y = f^*(X) = f(\theta^*, X)$	Theoretic D-TM whose algorithm is typically described in peer reviewed publications. The D-TM may e.g. implement a given WSTMe as instance of a suitable family of functions f by means of selected parameters θ^*. θ^* may be the result of an optimization (regression, control problem, ...).
$Y = f^\varsigma(X) = f(\theta^\varsigma, X, \zeta)$	Real D-TM where the software uncertainty ζ may affect both the function family f and the optimality of the selected parameters θ^ς.
$::\!\mid f(\theta, X, \zeta) \mid\!::^{sem}$	Semantically enhanced D-TM (e.g. SemAP). The D-TM is subject to the semantic checks *sem* as pre-, post-conditions and invariants on inputs, outputs and the D-TM itself: $Y = \; ::\!\mid f(\theta, X, \zeta) \mid\!::^{sem} \Leftrightarrow \begin{cases} Y = f(\theta, X, \zeta) \\ \Box sem(Y, f, \theta, X, \zeta) \end{cases}$

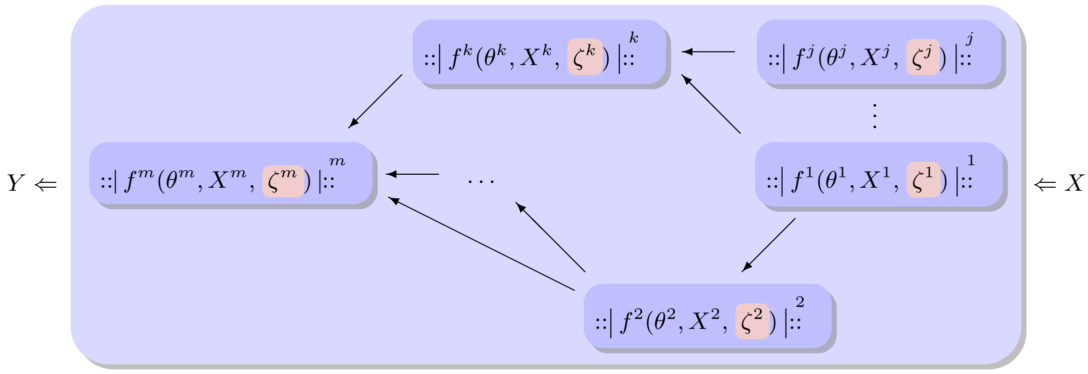
(b)

$$\text{where} \begin{cases} X \text{ is the input array of data } X = \{X_1, X_2, \cdots X_i \cdots X_n\} \\ X_i \in \mathbf{C}^{N_{i1} \times \cdots \times N_{in_i}} \text{ is a multi-dimensional array (e.g. a two-dimensional raster layer)} \\ Y \text{ is analogously the output array of data} \\ \text{the modal/deontic logic operator } \Box p \text{ means: it ought to be that } p. \end{cases}$$

The data and information flow of a black-box D-TM is often a (hidden) composition of D-TM modules:

$$Y \Leftarrow \; ::\!|\, f(\theta, X, \zeta)\, |\!::^{sem} \; \Leftarrow X$$

This chain of free-software D-TM modules (each of them semantically-enhanced) should be transparent:



Semantics and design diversity

Silent faults [63] are a critical class of software errors altering computation output without evident symptoms – such as computation premature interruption (exceptions, error messages, ...), obviously unrealistic results or computation patterns (e.g. noticeably shorter/longer or endless computations). As it has been underlined, "many scientific results are corrupted, perhaps fatally so, by undiscovered mistakes in the software used to calculate and present those results" [64]. Despite the ubiquity of software errors [61–69], the structural role of scientific software uncertainty seems dramatically underestimated [2,52]. Semantic D-TM modularization might help to catch at least a subset of silent faults, when misusing intermediate data outside the expected semantic context of a given D-TM module **(b)**.

Where the complexity and scale of WSTMe may lead unavoidable software-uncertainty to induce or worsen deep-uncertainty [2], techniques such as ensemble modelling may be recommendable [7,11,12]. Adapting those techniques for glancing at the software-uncertainty of a given WSTMe would imply availability of multiple instances (implementations) of the same abstract WSTMe. Independently re-implementing the same WSTMe (design diversity [70]) might of course be extremely expensive. However, partly independent re-implementations of critical D-TM modules may be more affordable and examples of comparison between supposedly equivalent D-TM algorithms seem to corroborate the interest of this research option [58,71,50].

References

[1] Casagrandi, R., Guariso, G., 2009. **Impact of ICT in environmental sciences: A citation analysis 1990-2007.** *Environmental Modelling & Software 24* (7), 865-871. doi: 10.1016/j.envsoft.2008.11.013 ↑

[2] de Rigo, D., (exp.) 2013. **Behind the horizon of reproducible integrated environmental modelling at European scale: ethics and practice of scientific knowledge freedom.** *F1000 Research.* Submitted ↑

[3] Gomes, C. P., 2009. **Computational sustainability: Computational methods for a sustainable environment, economy, and society.** *The Bridge 39* (4), 5-13. http://www.nae.edu/File.aspx?id=17673 ↑

[4] Easterbrook, S. M., Johns, T. C., 2009. **Engineering the software for understanding climate change.** *Computing in Science & Engineering 11* (6), 65-74. doi: 10.1109/MCSE.2009.193 ↑

[5] Hamarat, C., Kwakkel, J. H., Pruyt, E., 2012. **Adaptive robust design under deep uncertainty.** Technological Forecasting and Social Change. doi: 10.1016/j.techfore.2012.10.004 ↑

[6] Bankes, S. C., 2002. **Tools and techniques for developing policies for complex and uncertain systems.** *roc Natl Acad Sci U S A 99* (Suppl 3), 7263-7266. doi: 10.1073/pnas.092081399 ↑

[7] Kandlikar, M., Risbey, J., Dessai, S., 2005. **Representing and communicating deep uncertainty in climate-change assessments.** *Comptes Rendus Geoscience 337* (4), 443-455. doi: 10.1016/j.crte.2004.10.010 ↑

[8] de Rigo, D., Corti, P., Caudullo, G., McInerney, D., Di Leo, M., San-Miguel-Ayanz, J., 2013. **Toward Open Science at the European scale: Geospatial Semantic Array Programming for Integrated Environmental Modelling.** *Geophys Res Abstr 15*, 13245+. doi: 10.6084/m9.figshare.155703 ↑

[9] Rodriguez-Aseretto, D., Di Leo, M., de Rigo, D., Corti, P., McInerney, D., Camia, A., San Miguel-Ayanz, J., 2013. **Free and Open Source Software underpinning the European Forest Data Centre.** *Geophys Res Abstr 15*, 12101+. doi: 10.6084/m9.figshare.155700 ↑

[10] de Rigo, D., Corti, P., Caudullo, G., McInerney, D., Di Leo, M., San-Miguel-Ayanz, J., (exp. 2013). **Supporting Environmental Modelling and Science-Policy Interface at European Scale with Geospatial Semantic Array Programming.** In prep. ↑

[11] Lempert, R. J., 2002. **A new decision sciences for complex systems.** *Proc Natl Acad Sci U S A 99* (Suppl 3), 7309-7313. doi: 10.1073/pnas.082081699 ↑

[12] Gober, P., Kirkwood, C. W., 2010. **Vulnerability assessment of climate-induced water shortage in Phoenix.** *Proc Natl Acad Sci U S A 107* (50), 21295-21299. doi: 10.1073/pnas.0911113107 ↑

[13] de Rigo, D., 2012. **Semantic Array Programming for Environmental Modelling: Application of the Mastrave library.** In: Seppelt, R., Voinov, A. A., Lange, S., Bankamp, D. (Eds.), International Environmental Modelling and Software Society (iEMSs) 2012 International Congress on Environmental Modelling and Software. Managing Resources of a Limited Planet: Pathways and Visions under Uncertainty, Sixth Biennial Meeting. pp. 1167-1176. http://www.iemss.org/iemss2012/proceedings/D3_1_0715_deRigo.pdf ↑

[14] de Rigo, D., 2012. **Semantic Array Programming with Mastrave - Introduction to Semantic Computational Modelling.** http://mastrave.org/doc/MTV-1.012-1 ↑

[15] Free Software Foundation, 2012. **What is free software?** http://www.gnu.org/philosophy/free-sw.html (revision 1.118 archived at http://www.webcitation.org/6DXqCFAN3) ↑

[16] Stallman, R. M., 2009. **Viewpoint: Why "open source" misses the point of free software.** *Communications of the ACM 52* (6), 31-33. doi: 10.1145/1516046.1516058 (free access version: http://www.gnu.org/philosophy/open-source-misses-the-point.html) ↑

[17] Lempert, R., Schlesinger, M. E., 2001. **Climate-change strategy needs to be robust.** *Nature 412* (6845), 375. doi: 10.1038/35086617 ↑

[18] Shell, K. M., 2012. **Constraining cloud feedbacks.** *Science 338* (6108), 755-756. doi: 10.1126/science.1231083 ↑

[19] van der Sluijs, J. P., 2012. **Uncertainty and dissent in climate risk assessment: A Post-Normal perspective.** *Nature and Culture 7* (2), 174-195. doi: 10.3167/nc.2012.070204 ↑

[20] Lenton, T. M., Held, H., Kriegler, E., Hall, J. W., Lucht, W., Rahmstorf, S., Schellnhuber, H. J., 2008. **Tipping elements in the earth's climate system.** *Proc Natl Acad Sci U S A 105* (6), 1786-1793. doi: 10.1073/pnas.0705414105 ↑

[21] Hastings, A., Wysham, D. B., 2010. **Regime shifts in ecological systems can occur with no warning.** *Ecology Letters 13* (4), 464-472. doi: 10.1111/j.1461-0248.2010.01439.x ↑

[22] Barnosky, A. D., Hadly, E. A., Bascompte, J., Berlow, E. L., Brown, J. H., Fortelius, M., Getz, W. M., Harte, J., Hastings, A., Marquet, P. A., Martinez, N. D., Mooers, A., Roopnarine, P., Vermeij, G., Williams, J. W., Gillespie, R., Kitzes, J., Marshall, C., Matzke, N., Mindell, D. P., Revilla, E., Smith, A. B., 2012. **Approaching a state shift in earth's biosphere.** *Nature 486* (7401), 52-58. doi: 10.1038/nature11018 ↑

[23] Steffen, W., Persson, ., Deutsch, L., Zalasiewicz, J., Williams, M., Richardson, K., Crumley, C., Crutzen, P., Folke, C., Gordon, L., Molina, M., Ramanathan, V., Rockstrm, J., Scheffer, M., Schellnhuber, H. J., Svedin, U., 2011. **The anthropocene: From global change to planetary stewardship**. *AMBIO 40* (7), 739-761. doi: 10.1007/s13280-011-0185-x ↑

[24] Milly, P. C. D., Betancourt, J., Falkenmark, M., Hirsch, R. M., Kundzewicz, Z. W., Lettenmaier, D. P., Stouffer, R. J., 2008. **Stationarity is dead: Whither water management?** *Science 319* (5863), 573-574. doi: 10.1126/science.1151915 ↑

[25] Sloan, S., Pelletier, J., 2012. **How accurately may we project tropical forest-cover change? A validation of a forward-looking baseline for REDD.** *Global Environmental Change 22*(2), 440-453. doi: 10.1016/j.gloenvcha.2012.02.001 ↑

[26] Nabuurs, G.J., van Putten, B., Knippers, T.S., Mohren, G. M.J., 2008. **Comparison of uncertainties in carbon sequestration estimates for a tropical and a temperate forest.** *Forest Ecology and Management 256*(3), 237-245. doi: 10.1016/j.foreco.2008.04.010 ↑

[27] Green, D. G., Sadedin, S., 2005. **Interactions mattercomplexity in landscapes and ecosystems.** *Ecological Complexity 2* (2), 117-130. doi: 10.1016/j.ecocom.2004.11.006 ↑

[28] de Rigo, D., 2012. **Integrated Natural Resources Modelling and Management: minimal redefinition of a known challenge for environmental modelling.** Excerpt from the *Call for a shared research agenda toward scientific knowledge freedom*, Maieutike Research Initiative. `http://www.citeulike.org/groupfunc/15400/home` ↑

[29] Baker, R., Koch, F., Kriticos, D., Rafoss, T., Venette, R., van der Werf, W. (Eds.), 2012. **Advancing risk assessment models for invasive alien species in the food chain: contending with climate change, economics and uncertainty.** *Bioforsk FOKUS 7.* Bioforsk, Frederik A. Dahls vei 20, 1432 s, Norway. `http://www.pestrisk.org/2012/BioforskFOKUS7-10_IPRMW-VI.pdf` ↑

[30] de Rigo, D., Caudullo, G., San-Miguel-Ayanz, J., Stancanelli, G., 2012. **Mapping European forest tree species distribution to support pest risk assessment.** In: Baker, R., Koch, F., Kriticos, D., Rafoss, T., Venette, R., van der Werf, W. (Eds.), Advancing risk assessment models for invasive alien species in the food chain: contending with climate change, economics and uncertainty. *Bioforsk FOKUS 7.* Bioforsk, Frederik A. Dahls vei 20, 1432 s, Norway. `http://www.pestrisk.org/2012/BioforskFOKUS7-10_IPRMW-VI.pdf` ↑

[31] Thompson, I., Mackey, B., McNulty, S., Mosseler, A., 2009. **Forest resilience, biodiversity, and climate change: a synthesis of the biodiversity/resilience/stability relationship in forest ecosystems.** Vol. 43 of Technical Series. Secretariat of the Convention on Biological Diversity. ISBN: 9292251376 ↑

[32] Center for International Forestry Research., FAO Regional Office for Asia and the Pacific, 2005. **Forests and floods: drowning in fiction or thriving on facts?** Center for International Forestry Research; Food and Agriculture Organization of the United Nations, Regional Office for Asia and the Pacific. `http://www.worldcat.org/isbn/9793361646` ↑

[33] Bonan, G. B., 2008. **Forests and climate change: Forcings, feedbacks, and the climate benefits of forests.** *Science 320* (5882), 1444-1449. doi: 10.1126/science.1155121 ↑

[34] Ferreira, L., Constantino, M. F., Borges, J. G., Garcia-Gonzalo, J., 2012. **A stochastic dynamic programming approach to optimize Short-Rotation coppice systems management scheduling: An application to eucalypt plantations under wildfire risk in portugal.** *Forest Science 58* (4), 353–365. doi: 10.5849/forsci.10-084 ↑

[35] de Rigo, D., Rizzoli, A. E., Soncini-Sessa, R., Weber, E., Zenesi, P., 2001. **Neuro-dynamic programming for the efficient management of reservoir networks.** In: Proceedings of MODSIM 2001, International Congress on Modelling and Simulation. Vol. 4. Modelling and Simulation Society of Australia and New Zealand, pp. 1949-1954. `http://mpra.ub.uni-muenchen.de/42233/` ↑

[36] Bond, C. A., Champ, P., Meldrum, J., Schoettle, A., 2011. **Investigating the optimality of proactive management of an invasive forest pest.** In: Keane, R. E., Tomback, D. F., Murray, M. P., Smith, C. M. (Eds.), The future of high-elevation, five-needle white pines in Western North America: Proceedings of the High Five Symposium. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, pp. 295-302. `http://www.treesearch.fs.fed.us/pubs/38241` ↑

[37] de Rigo, D., Castelletti, A., Rizzoli, A. E., Soncini-Sessa, R., Weber, E., 2005. **A selective improvement technique for fastening neuro-dynamic programming in water resources network management**. *IFAC-PapersOnLine 16* (1), 7–12. International Federation of Automatic Control (IFAC). doi: 10.3182/20050703-6-CZ-1902.02172 ↑

[38] Phillis, Y. A., Kouikoglou, V. S., 2012. **System-of-Systems hierarchy of biodiversity conservation problems.** *Ecological Modelling 235-236*, 36-48. doi: 10.1016/j.ecolmodel.2012.03.032 ↑

[39] Cavallo, A., Nardo, A., 2008. **Optimal fuzzy management of reservoir based on genetic algorithm.** In: Lowen, R., Verschoren, A. (Eds.), Foundations of Generic Optimization. Vol. 24 of Mathematical Modelling: Theory and Applications. Springer Netherlands, pp. 139-159. doi: 10.1007/978-1-4020-6668-9_2 ↑

[40] Castelletti, A., deRigo, D., Tepsich, L., Soncini-Sessa, R., Weber, E., 2008. **On-Line design of water reservoir policies based on inflow prediction.** *IFAC-PapersOnLine 17* (1), 14540–14545. International Federation of Automatic Control (IFAC). doi: 10.3182/20080706-5-KR-1001.02463 ↑

[41] Kempeneers, P., Sedano, F., Seebach, L. M., Strobl, P., San-Miguel-Ayanz, J., 2011. **Data fusion of different spatial resolution remote sensing images applied to Forest-Type mapping.** *IEEE Transactions on Geoscience and Remote Sensing 49* (12), 4977-4986. doi: 10.1109/TGRS.2011.2158548 ↑

[42] Sedano, F., Kempeneers, P., Strobl, P., McInerney, D., San-Miguel-Ayanz, J., 2012. **Increasing spatial detail of burned scar maps using IRSAWiFS data for mediterranean Europe.** *Remote Sensing 4* (3), 726-744. doi: 10.3390/rs4030726 ↑

[43] de Rigo, D., Bosco, C., 2011. **Architecture of a Pan-European Framework for Integrated Soil Water Erosion Assessment.** *IFIP Advances in Information and Communication Technology 359*, 310-318. Springer. doi: 10.1007/978-3-642-22285-6_34 ↑

[44] Voinov, A., Shugart, H. H., 2013. **'integronsters', integral and integrated modeling.** *Environmental Modelling & Software 39*, 149-158. doi: 10.1016/j.envsoft.2012.05.014 ↑

[45] Mendoza, G. A., Martins, H., 2006. **Multi-criteria decision analysis in natural resource management: A critical review of methods and new modelling paradigms.** *Forest Ecology and Management 230* (1-3), 1-22. doi: 10.1016/j.foreco.2006.03.023 ↑

[46] O'Farrell, P. J., Anderson, P. M. L., 2010. **Sustainable multifunctional landscapes: a review to implementation.** *Current Opinion in Environmental Sustainability 2* (1-2), 59-65. doi: 10.1016/j.cosust.2010.02.005 ↑

[47] Dale, V. H., Beyeler, S. C., 2001. **Challenges in the development and use of ecological indicators.** *Ecological Indicators 1* (1), 3-10. doi: 10.1016/S1470-160X(01)00003-6 ↑

[48] Gilbert, N., 2010. **Balancing water supply and wildlife.** *Nature.* doi: 10.1038/news.2010.505 ↑

[49] Morin, A., Urban, J., Adams, P. D., Foster, I., Sali, A., Baker, D., Sliz, P., 2012. **Shining light into black boxes.** *Science 336* (6078), 159-160. doi: 10.1126/science.1218263 ↑

[50] Barnes, N., Jones, D., 2011. **Clear climate code: Rewriting legacy science software for clarity.** *Software, IEEE 28* (6), 36-42. doi: 10.1109/MS.2011.113 ↑

[51] Sanders, R., Kelly, D., 2008. **Dealing with risk in scientific software development.** *Software, IEEE 25* (4), 21-28. doi: 10.1109/MS.2008.84 ↑

[52] Cerf, V. G., 2012. **Where is the science in computer science?** *Commun. ACM 55* (10), 5. doi: 10.1145/2347736.2347737 ↑

[53] Pincas, U., 2011. **Program verification and functioning of operative computing revisited: How about mathematics engineering?** *Minds and Machines 21* (2), 337-359. doi: 10.1007/s11023-011-9237-z ↑

[54] Sanders, P., 2009. **Algorithm engineering an attempt at a definition.** In: Albers, S., Alt, H., Nher, S. (Eds.), Efficient Algorithms. Vol. 5760 of Lecture Notes in Computer Science. Springer Berlin Heidelberg, pp. 321-340. doi: 10.1007/978-3-642-03456-5_22 ↑

[55] Kleiner, K., 2011. **Data on demand.** *Nature Climate Change 1* (1), 10-12. doi: 10.1038/nclimate1057 ↑

[56] Nature, 2011. **Devil in the details.** *Nature 470* (7334), 305-306. doi: 10.1038/470305b ↑

[57] Peng, R. D., 2011. **Reproducible research in computational science.** *Science 334* (6060), 1226-1227.doi: 10.1126/science.1213847 ↑

[58] Cai, Y., Judd, K. L., Lontzek, T. S., 2012. **Open science is necessary.** *Nature Climate Change 2* (5), 299. doi: 10.1038/nclimate1509 ↑

[59] Ghisla, A., Rocchini, D., Neteler, M., Frster, M., Kleinschmit, B., 2012. **Species distribution modelling and open source GIS: why are they still so loosely connected?** In: Seppelt, R., Voinov, A. A., Lange, S., Bankamp, D. (Eds.), International Environmental Modelling and Software Society (iEMSs) 2012 International Congress on Environmental Modelling and Software. Managing Resources of a Limited Planet: Pathways and Visions under Uncertainty, Sixth Biennial Meeting. pp. 1481-1488. `http://www.iemss.org/iemss2012/proceedings/D6_0897_Ghisla_et_al.pdf` ↑

[60] Iverson, K. E., 1980. **Notation as a tool of thought.** *Communications of the ACM 23* (8), 444-465. http://awards.acm.org/images/awards/140/articles/9147499.pdf ↑

[61] Lehman, M. M., 1989. **Uncertainty in computer application and its control through the engineering of software.** *J. Softw. Maint: Res. Pract. 1* (1), 3-27. doi: 10.1002/smr.4360010103 ↑

[62] Lehman, M. M., Ramil, J. F., 2002. **Software uncertainty.** In: Bustard, D., Liu, W., Sterritt, R. (Eds.), Soft-Ware 2002: Computing in an Imperfect World. Vol. 2311 of Lecture Notes in Computer Science. Springer Berlin / Heidelberg, Ch. 14, pp. 477-514. doi: 10.1007/3-540-46019-5_14 ↑

[63] Hook, D., Kelly, D., 2009. **Testing for trustworthiness in scientific software.** In: Software Engineering for Computational Science and Engineering, 2009. SECSE '09. ICSE Workshop on. IEEE, Washington, DC, USA, pp. 59-64. doi: 10.1109/SECSE.2009.5069163 ↑

[64] Hatton, L., 2007. **The chimera of software quality.** *Computer 40* (8), 104-103. doi: 10.1109/MC.2007.292 ↑

[65] Hatton, L., 1997. **The t experiments: errors in scientific software.** *Computational Science & Engineering, IEEE* 4 (2), 27-38. doi: 10.1109/99.609829 ↑

[66] Hatton, L., 2012. **Defects, scientific computation and the scientific method uncertainty quantification in scientific computing.** *IFIP Advances in Information and Communication Technology 377*, 123–138. Springer. doi: 10.1007/978-3-642-32677-6_8 ↑

[67] Lehman, M. M., 1996. **Laws of software evolution revisited software process technology.** In: Montangero, C. (Ed.), Software Process Technology. Vol. 1149 of Lecture Notes in Computer Science. Springer Berlin/Heidelberg, Ch. 12, pp. 108-124. doi: 10.1007/BFb0017737 ↑

[68] Oberkampf, W. L., DeLand, S. M., Rutherford, B. M., Diegert, K. V., Alvin, K. F., 2002. **Error and uncertainty in modeling and simulation.** *Reliability Engineering & System Safety 75* (3), 333-357. doi: 10.1016/S0951-8320(01)00120-X ↑

[69] Wilson, G., 2006. **Where's the real bottleneck in scientific computing?** *American Scientist 94* (1), 5+. doi: 10.1511/2006.1.5 ↑

[70] Rebaudengo, M., Reorda, M., Violante, M., 2011. **Software-Level Soft-Error mitigation techniques.** In: Nicolaidis, M. (Ed.), Soft Errors in Modern Electronic Systems. Vol. 41 of Frontiers in Electronic Testing. Springer US, pp. 253-285. doi: 10.1007/978-1-4419-6993-4_9 ↑

[71] Beaudette, D., 2008. **Simple comparison of two Least-Cost path approaches.** In: Open Source Software Tools for Soil Scientists. http://casoilresource.lawr.ucdavis.edu/drupal/node/544 (archived at: http://www.webcitation.org/6D0LHBRXW) ↑